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RESEARCH AND DEVELOPMENT TECHNICAL REPORT
ECOM-0381-3

EVALUATION OF ATMOSPHERIC TRANSPORT AND DIFFUSION

SEMI-ANNUAL REPORT

By
William H. Clayton, Principal Investigator
Tom E. Sanford and Bernice Ackerman

April 1970

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

Contract DAAB07-68-C-0381

DEPARTMENTS OF METEOROLOGY AND OCEANOGRAPHY
TEXAS A&M UNIVERSITY
College Station, Texas

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70

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April 1970

EVALUATION OF ATMOSPHERIC TRANSPORT AND DIFFUSION

Semi-Annual Report

15 June 1969 to 15 December 1969

Report No. 3

Contract No. DAAB07-68-C-0381

Project 586

Reference 70-3-T

William H. Clayton, Principal Investigator

T. E. Sanford and Bernice Ackerman

TEXAS A & M RESEARCH FOUNDATION

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For

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ABSTRACT

This report summarizes the activities carried out under Signal Corps Contract No. DAAB07-68-C-0381 (Texas A&M Research Foundation Project 586) during the contract period 15 June 1969 through 15 December 1969.

Activities during this period have centered on preparation of the equations for the forested boundary layer for solution on the general purpose analog computer at Texas A&M University. These expressions, which were presented in Semi-Annual Report 2, have been programmed for a seven-level simulation, three in the forest and four in the free air above, and for the surface and free air-canopy interfaces. The wiring of the patchboards is proceeding as the wiring diagrams are completed.

Some qualitative diffusion tests were carried out in the tropical forest in the Panama Canal Zone. Visual and photographic observations have been summarized.

ACKNOWLEDGEMENT

The research reported herein has been performed under Contract DAAB07-68-C-0381, sponsored by the U. S. Army Electronics Laboratories at Fort Monmouth, New Jersey; however, personnel and equipment support for the General Purpose Analog Computer facility utilized in this research is also provided by the Research Council of Texas A&M University.

TABLE OF CONTENTS

LIST OF TABLES

I. Introduction

An experimental system of equations has been developed to simulate the atmosphere within a forest and in the atmospheric boundary layer just above the forest. These equations, accompanied by a discussion of the physical considerations used in the development of the set, were given in Semi-Annual Report 2. They are repeated in Appendix A for convenient referral. Except for some minor changes in symbology, the only modification has been in the calculation of stress at the top of the canopy. In the new set, a logarithmic distribution of wind speed, rather than a linear one, has been assumed.

The essential parts of the formulation are the equations which define the temporal variations of momentum, temperature, and vapor pressure in the forest and in the free air above (equations 1f-4f, 1-4) and those which represent the heat balance at the top of the canopy and at the earth's surface (equations 19, 20, 18f, 19f). Most of the other expressions define the various terms in these basic equations or are approximations which simplify their solution. Many of these are standard, e.g., the relationship between specific humidity and vapor pressure (equation 11); others are specific for this particular problem as in the expression for the momentum exchange coefficient in the free air-canopy section (equation 37).

The principle activities over the past six months have been devoted to the task of programming the equations for solution on the general purpose analog computer at Texas A&M. The

scaled analog format which is being wired for the simulation is discussed in section II of this report. Section III contains a summary of the visual and photographic observations made during some qualitative diffusion tests carried out in the Panama Canal Zone forest during August.

II. Scaled Analog Format

The general analog form for those equations which will be solved on the computer are given in Appendix B. Relationships such as equations (11) and (13) which define terms in other, more basic, equations or which are used to simplify them are not included in the listing. The numbering used in Appendix A is retained in Appendix B with the prefix "a" to indicate analog format. Thus, equation (a7) is the analog equivalent of the mathematical form, equation (7), in Appendix A.

The transformation from mathematical to analog format is effected primarily by the integration of the equation. Where necessary, simpler or more readily solved forms of the individual terms are substituted for the original ones. Thus in equation (a1) the value of the x-component of the wind at any time, t, is given by the integration, from initial time to time t, of the several terms on the right. The initial conditions have been omitted as understood, but, of course, will be included in the simulation. Finite differences have been used as an approximation of differentiation in the vertical, usually with the implicit assumption of linear variation of the meteorological parameter between the grid points. The individual terms in each equation will be discussed below, after the scaled equations are given.

Subscript indices are used to indicate the height at which the various parameters are computed. The subscript "j" signifies the level at which the simulation of the primary variables is carried

out. The bottom of the layer containing the j^{th} level is signified by the double subscript "ij" and the top by the double subscript "jk". Thus, the j^{th} level, at height z_j, lies between height z_{ij} at the bottom of the layer and height z_{jk} at the top of the j^{th} layer. The depth of that layer is indicated by Δz_j. The bottom of the layer for the j^{th} level coincides with the top of the layer for the i^{th} level ($i=j-1$). Thus, $\tau_{x,ij}$ is the x-component of the shearing stress at the interface of the layers containing the i^{th} and j^{th} levels. The reader is referred to figure 1 for further clarification of the concepts of levels and layers and the usage of the indices "j" and "ij". The primary variables, u, v, T, and e, are predicted for the levels j while the stresses and fluxes are computed at the interface of the layers containing successive levels, that is, at heights indicated by the double index ij.

In preparing for the simulation each of the equations in Appendix B was expanded to account for the multiplicity of levels. The expanded set has been scaled so that the voltage representing each variable will cover as large a range as feasible during the simulation without overloading the amplifiers. The standard scaling for the general purpose analog computer at Texas A&M is based on a reference unit of 100 volts. The scale factors which have been adopted are estimates of the maximum values (absolute) which the meteorological variables are likely to attain in this simulation. These are represented on the computer as 100 volt outputs.

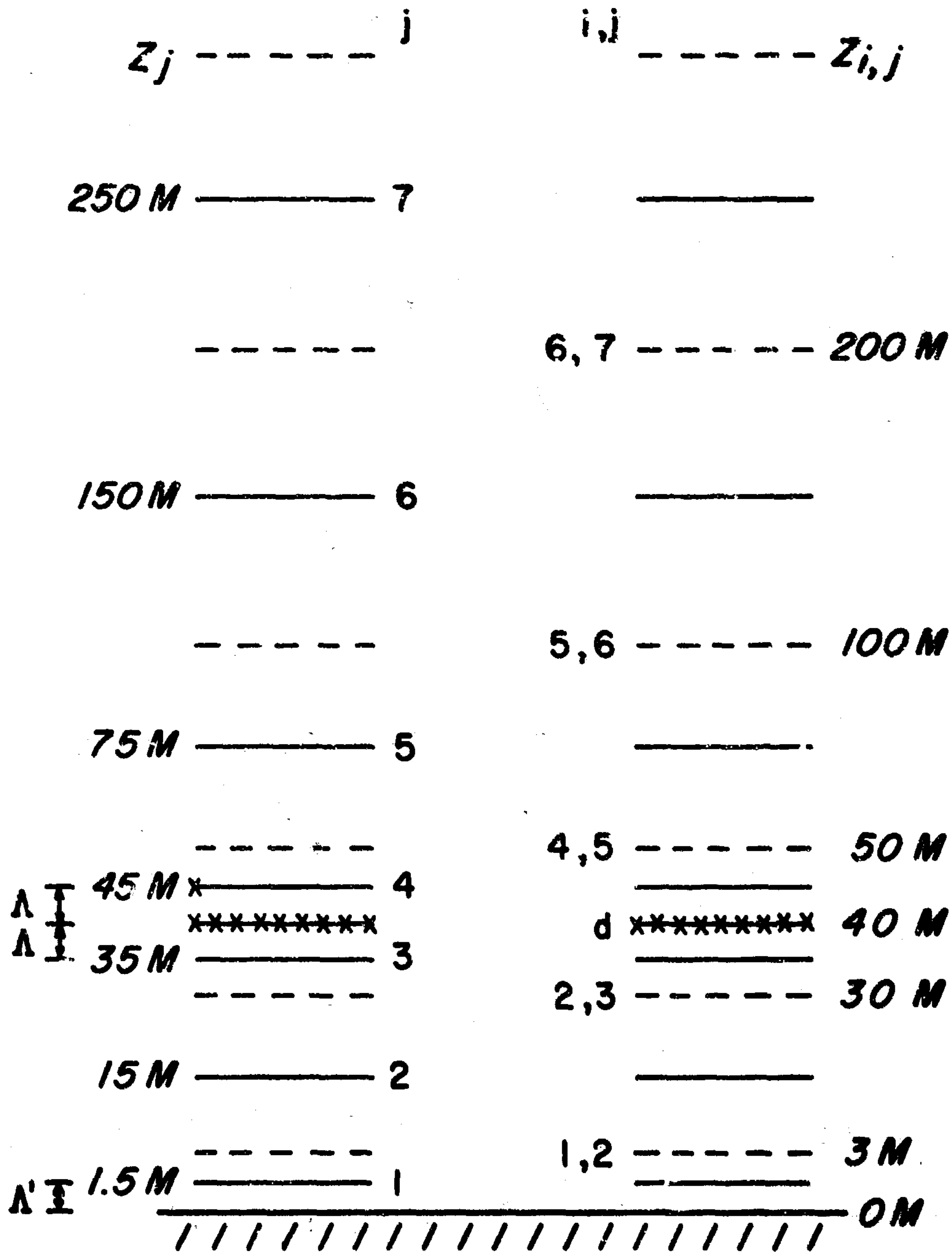

Figure 1. Schematic presentation of the levels and layers of the forest model to be used for the initial tests. Levels are indicated by solid lines and layer interfaces by dashed lines. The numbers in the center are the indices used to signify the levels and layer interfaces at heights given along the edges. The top of the canopy is at 40 m.

Tentative scaling factors for all variables are listed in Table 1, along with certain other machine constants. These are subject to change should the test solutions indicate serious over- or under-scaling of the parameters. The time scaling, computer time versus real time, of 1440 to 1 will be used in the initial simulation. That is, the computer solution will be 1440 times faster than the real problem time, so that an eight-hour prediction can be obtained in about 20 seconds.

The scaled equations are given in Table 2. They are numbered to agree with the corresponding mathematical form in Appendix A, with the prefix "s" to indicate scaled form. Thus, the scaled form of the mathematical expression for the x-component of the shearing stress (equation 7, Appendix A) is equation (s7) in Table 2, just as the analog form is equation (a7) in Appendix B.

In the scaled representation the forested boundary layer is treated in seven layers, three in the forest itself and four in the free air above the canopy (figure 1). The wind components, temperature and vapor pressure at the four levels above the forest are found from equations (s1) - (s4) and those at the three levels in the forest in equations (s1f) - (s4f). The stresses and the fluxes of heat and momentum at the layer interfaces are given in equations (s7) - (s10) for the region above the canopy and in equations (s7f), (s8f), (s11f), and (s12f) for the forest atmosphere. In addition the equations which provide the temperatures and vapor pressures, the stresses, and the heat and vapor fluxes,

Table 1. Scale factor and constants employed in the forest boundary layer simulation.

A. Scale Factors

$D_{\Lambda'}$	:	10 cm/sec	R_N	:	0.05 cal/cm^2 sec
e	:	100 mb	S_{Λ}	:	20 cm/sec
F_x, F_y	:	1000 cm/sec^2	$S_{\Lambda'}$	:	10 cm/sec
FCG	:	100 m/100 km	T	:	50°C
ICG	:	100 m/100 km	time	:	1440:1
K_m	:	50,000 cm^2/sec	u,v	:	50 m/sec (free air)
q_o	:	0.05 cal/cm^2 sec		:	10 m/sec (forest)
q_s	:	0.05 cal/cm^2 sec	τ_x, τ_y	:	20 dynes/cm^2

B. Constants

a = 0.6210	P = 86,400 sec
C_p = 0.2400 cal/gm deg	p_o = 1012 mb
g = 980 cm/sec^2	Z = 1050 m
I = 0.0330 cal/cm^2 sec	σ = 1.354x10^{-12} cal/cm^2 sec deg
k = 0.4000	ω = 7.3x10^{-5} rad/sec
L = 593.3 cal/gm	ρ = 1.2x10^{-3} gm/cm^3

Table 2. Scaled analog format for equations to be wired on the computer. Coefficients, c, are given in Table 3. See text for discussion and explanation.

j	i	z_j (m)	z_{ij} (m)	A. Free air, $z \geqslant (d + \Lambda)$	
7		250m		$1440\left(\frac{u_7}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472} - \frac{\Delta\left(g\frac{\partial h}{\partial x}\right)_7}{4.34} + c_1\left(\frac{v_7}{5000}\right) + c'_{2,7}\left(\frac{\tau_{x,67}}{20}\right) - \left(\frac{\alpha'_7 u_7 - \beta'_7 v_7}{3.472}\right)\right]$	
6		150		$1440\left(\frac{u_6}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472} - \frac{\left(\Delta g\frac{\partial h}{\partial x}\right)_6}{4.34} + c_1\left(\frac{v_6}{5000}\right) + c_{2,6}\left(\frac{\tau_{x,67} - \tau_{x,56}}{20}\right)\right.$	
				$\left. - c_{3,6}\left(\frac{\alpha'_4 u_4 - \beta'_4 v_4}{3.472}\right) - c_{4,6}\left(\frac{\alpha'_7 u_7 - \beta'_7 v_7}{3.472}\right)\right]$	(s1)
5		75		$1440\left(\frac{u_5}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472} - \frac{\left(\Delta g\frac{\partial h}{\partial x}\right)_5}{4.34} + c_1\left(\frac{v_5}{5000}\right) + c_{2,5}\left(\frac{\tau_{x,56} - \tau_{x,45}}{20}\right)\right.$	
				$\left. - c_{3,5}\left(\frac{\alpha'_4 u_4 - \beta'_4 v_4}{3.472}\right) - c_{4,5}\left(\frac{\alpha'_7 u_7 - \beta'_7 v_7}{3.472}\right)\right]$	

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
4		45		$1440\left(\frac{u_4}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472} + c_1\left(\frac{v_4}{5000}\right) + c_{2,4}\left(\frac{\tau_{x,45} - \tau_{x,d}}{20}\right) - \left(\frac{\alpha_4' u_4 - \beta_4' v_4}{3.472}\right)\right]$
7		250		$1440\left(\frac{v_7}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472} - \frac{\left(\Delta g\frac{\partial h}{\partial y}\right)_7}{4.34} - c_1\left(\frac{u_7}{5000}\right) + c_{2,7}'\left(\frac{\tau_{y,67}}{20}\right) - \left(\frac{\alpha_7' v_7 + \beta_7' u_7}{3.472}\right)\right]$
6		150		$1440\left(\frac{v_6}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472} - \frac{\left(\Delta g\frac{\partial h}{\partial y}\right)_6}{4.34} - c_1\left(\frac{u_6}{5000}\right) + c_{2,6}\left(\frac{\tau_{y,67} - \tau_{y,56}}{20}\right) - c_{3,6}\left(\frac{\alpha_4' v_4 + \beta_4' u_4}{3.472}\right) - c_{4,6}\left(\frac{\alpha_7' v_7 + \beta_7' u_7}{3.472}\right)\right]$ (s2)
5		75		$1440\left(\frac{v_5}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472} - \frac{\left(\Delta g\frac{\partial h}{\partial y}\right)_5}{4.34} - c_1\left(\frac{u_5}{5000}\right) + c_{2,5}\left(\frac{\tau_{y,56} - \tau_{y,45}}{20}\right) - c_{3,5}\left(\frac{\alpha_4' v_4 + \beta_4' u_4}{3.472}\right) - c_{4,7}\left(\frac{\alpha_7' v_7 + \beta_7' u_7}{3.472}\right)\right]$

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
4		45		$1440\left(\frac{v_4}{5000}\right) = \int\left[-\frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472} - c_1\left(\frac{u_4}{5000}\right) + c_{2,4}\left(\frac{\tau_{y,45} - \tau_{y,d}}{20}\right) - \left(\frac{\alpha_4' v_4 + \beta_4' u_4}{3.472}\right)\right]$
7		250		$1440\left(\frac{T_7}{50}\right) = \int\left[\frac{R}{.03472} - c_{5,7}'\left(\frac{q_{c,67}}{.05}\right) - \left(\frac{u_7\left(\frac{\partial T}{\partial x}\right)_7 + v_7\left(\frac{\partial T}{\partial y}\right)_7}{.03472}\right)\right]$
6		150		$1440\left(\frac{T_6}{50}\right) = \int\left[\frac{R}{.03472} - c_{5,6}\left(\frac{q_{c,67} - q_{c,56}}{.05}\right) - c_{3,6}\left(\frac{u_4\left(\frac{\partial T}{\partial x}\right)_4 + v_4\left(\frac{\partial T}{\partial y}\right)_4}{.03472}\right)\right.$ $\left.-c_{4,6}\left(\frac{u_7\left(\frac{\partial T}{\partial x}\right)_7 + v_7\left(\frac{\partial T}{\partial y}\right)_7}{.03472}\right)\right]$ (s3)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
5		75		$1440\left(\frac{T_5}{50}\right) = \int \left[\frac{R}{.03472} - c_{5,5}\left(\frac{q_{c,56} - q_{c,45}}{.05}\right) - c_{3,5}\left(\frac{u_4\left(\frac{\partial T}{\partial x}\right)_4 + v_4\left(\frac{\partial T}{\partial y}\right)_4}{.03472}\right) - c_{4,5}\left(\frac{u_7\left(\frac{\partial T}{\partial x}\right)_7 + v_7\left(\frac{\partial T}{\partial y}\right)_7}{.03472}\right) \right]$
4		50		$1440\left(\frac{T_4}{50}\right) = \int \left[\frac{R}{.03472} - c_{5,4}\left(\frac{q_{c,45} - q_{c,d+}}{.05}\right) - \left(\frac{u_4\left(\frac{\partial T}{\partial x}\right)_4 + v_4\left(\frac{\partial T}{\partial y}\right)_4}{.03472}\right) \right]$
7		250		$1440\left(\frac{e_7}{100}\right) = \int \left[-c'_{6,7}\left(\frac{q_{e,67}}{.05}\right) - \left(\frac{u_7\left(\frac{\partial e}{\partial x}\right)_7 + v_7\left(\frac{\partial e}{\partial y}\right)_7}{.06944}\right) \right]$
6		150		$1440\left(\frac{e_6}{100}\right) = \int \left[-c_{6,6}\left(\frac{q_{e,67} - q_{e,56}}{.05}\right) - c_{3,6}\left(\frac{u_4\left(\frac{\partial e}{\partial x}\right)_4 + v_4\left(\frac{\partial e}{\partial y}\right)_4}{.06944}\right) - c_{4,6}\left(\frac{u_7\left(\frac{\partial e}{\partial x}\right)_7 + v_7\left(\frac{\partial e}{\partial y}\right)_7}{.06944}\right) \right]$ (s4)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
5		75		$1440 \left(\frac{e_5}{100}\right) = \int \left[- c_{6,5}\left(\frac{q_{e,56} - q_{e,45}}{.05}\right) - c_{3,5}\left(\frac{u_4\left(\frac{\partial e}{\partial x}\right)_4 + v_4\left(\frac{\partial e}{\partial y}\right)_4}{.06944}\right) - c_{4,5}\left(\frac{u_7\left(\frac{\partial e}{\partial x}\right)_7 + v_7\left(\frac{\partial e}{\partial y}\right)_7}{.06944}\right)\right]$
4		45		$1440 \left(\frac{e_4}{100}\right) = \int \left[- c_{6,4}\left(\frac{q_{e,45} - q_{e,d+}}{.05}\right) - \left(\frac{u_4\left(\frac{\partial e}{\partial x}\right)_4 + v_4\left(\frac{\partial e}{\partial y}\right)_4}{.06944}\right)\right]$
7	6		200	$\left(\frac{\tau_{x,67}}{20}\right) = c_{7,7}\left(\frac{K_{m,4}}{50,000}\right)\left(\frac{u_7 - u_6}{5000}\right)$
6	5		100	$\left(\frac{\tau_{x,56}}{20}\right) = c_{7,6}\left(\frac{K_{m,4}}{50,000}\right)\left(\frac{u_6 - u_5}{5000}\right)$ (s7)
5	4		50	$\left(\frac{\tau_{x,45}}{20}\right) = c_{7,5}\left(\frac{K_{m,4}}{50,000}\right)\left(\frac{u_5 - u_4}{5000}\right)$
7	6		200	$\left(\frac{\tau_{y,67}}{20}\right) = c_{7,7}\left(\frac{K_{m,4}}{50,000}\right)\left(\frac{v_7 - v_6}{5000}\right)$

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)		
6	5		100	$\left(\frac{\tau_{v,56}}{20}\right) = c_{7,6}\left(\frac{K_{m,4}}{50{,}000}\right)\left(\frac{v_6 - v_5}{5000}\right)$	(s8)
5	4		50	$\left(\frac{\tau_{v,45}}{20}\right) = c_{7,5}\left(\frac{K_{m,4}}{50{,}000}\right)\left(\frac{v_5 - v_4}{5000}\right)$	
7	6		200	$\left(\frac{q_{c,67}}{.05}\right) = -c_{8,7}\left(\frac{K_{h,4}}{50{,}000}\right)\left(\frac{T_7 - T_6}{50}\right)$	
6	5		100	$\left(\frac{q_{c,65}}{.05}\right) = -c_{8,6}\left(\frac{K_{h,4}}{50{,}000}\right)\left(\frac{T_6 - T_5}{50}\right)$	(s9)
5	4		50	$\left(\frac{q_{c,54}}{.05}\right) = -c_{8,5}\left(\frac{K_{h,4}}{50{,}000}\right)\left(\frac{T_5 - T_4}{50}\right)$	
7	6		200	$\left(\frac{q_{e,67}}{.05}\right) = c_{9,7}\left(\frac{K_{v,4}}{50{,}000}\right)\left[c_{10,7}\left(\frac{e_6}{100}\right) - \left(\frac{e_7}{100}\right)\right]$	(s10)
6			100	$\left(\frac{q_{e,56}}{.05}\right) = c_{9,6}\left(\frac{K_{v,4}}{50{,}000}\right)\left[c_{10,6}\left(\frac{e_5}{100}\right) - \left(\frac{e_6}{100}\right)\right]$	

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
5	4		50	$\left(\frac{q_{e,45}}{.05}\right) = c_{9,5}\left(\frac{K_{v,4}}{50,000}\right)\left[c_{10,5}\left(\frac{e_4}{100}\right) - \left(\frac{e_5}{100}\right)\right]$
7	6		200	$K_{m,67} = b'_{67}\ K_{m,4}$
6	5		100	$K_{m,56} = b'_{56}\ K_{m,4}$ (s15)
5	4		50	$K_{m,45} = b'_{56}\ K_{m,4}$
				$\left(\Delta g\ \frac{\partial h}{\partial x}\right)_j = \frac{g}{.8}\left[c_{11,j}\left(\frac{\partial T}{\partial x}\right)_4 + c_{12,j}\left(\frac{\partial T}{\partial y}\right)_7\right]$
				$\left(\Delta g\ \frac{\partial h}{\partial y}\right)_j = \frac{g}{.8}\left[c_{11,j}\left(\frac{\partial T}{\partial x}\right)_4 + C_{12,j}\left(\frac{\partial T}{\partial y}\right)_7\right]$ (s17)
				$\frac{\left(g\ \frac{\partial h}{\partial x}\right)_o}{3.472} = \frac{g \times 10^{-3}}{3.472}\left[\frac{ICG \sin (ICG)}{100} + \left\{\left[\frac{FCG \sin (FCG)}{100} - \frac{ICG \sin (ICG)}{100}\right]\frac{1440}{\Delta t}\right]$

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
				$\frac{\left(g\frac{\partial h}{\partial y}\right)_o}{3.472} = \frac{g \times 10^{-3}}{3.472}\left[\frac{ICG \cos (ICG)}{100} + \int \left[\frac{FCG \cos (FCG)}{100} - \frac{ICG \cos (ICG)}{100}\right]\frac{1440}{\Delta t}\right]$ (s18)
j	i	z_j (m)	z_{ij} (m)	B. Free air - canopy section, z = d
d		40		$\frac{R_N}{.05} = \left(\frac{q_{c,d+}}{.05}\right) + \left(\frac{q_{e,d+}}{.05}\right) + \left(\frac{q_{c,d-}}{.05}\right) + \left(\frac{q_{e,d-}}{.05}\right)$ (s19) $\frac{R_N}{.05} = \left(\frac{I}{.05}\right)(1 - J)\ \psi\ e^{-N}\ F_c \cos \zeta + \left(\frac{\sigma T_4^4}{.05}\right)\left(m + 10n\sqrt{\frac{e_4'}{100}}\right) - \varepsilon\left(\frac{\sigma T_d^4}{.05}\right)$ (s20) $\frac{\cos \zeta}{1} = \frac{\sin \phi}{1}\ \frac{\sin \delta}{1} + \frac{\cos \phi}{1}\ \frac{\cos \delta}{1}\ \frac{\cos(15[t-12])}{1}$ (s22) $\left(\frac{q_{c,d+}}{.05}\right) = c'_{8,4}\left(\frac{K_{h,4}}{50,000}\right)\left(\frac{T_d - T_4}{50}\right)$ (s25)

Table 2. Continued

j†	i	z_j (m)	z_{ij} (m)			
				$\left(\frac{q_{c,d-}}{.05}\right) = c'_{8,d}\left(\frac{K_{h,4}}{50,000}\right)\left[\frac{T_d - T_3}{.05}\right]$		(s26)
				$\left(\frac{q_{e,d+}}{.05}\right) = c'_{9,4}\left(\frac{K_{v,4}}{50,000}\right)\left[\left(\frac{e_d}{100}\right) - \left(\frac{e_4}{100}\right)\right]$		(s27)
				$\left(\frac{q_{e,d-}}{.05}\right) = c'_{9,d}\left(\frac{K_{v,4}}{50,000}\right)\left[\frac{e_d}{100} - \frac{e_3}{100}\right]$		(s28)
				$\left(\frac{e_d}{100}\right) = \frac{e_{d,s}}{100} - \frac{.0005}{\xi}\left(\frac{q_{e,d+}}{.05}\right)$	$q_{e,d+} > 0$	(s29)
				$\left(\frac{e_d}{100}\right) = \frac{e_{d,s}}{100}$	$q_{e,d} < 0$	(s30)
				$\left(\frac{e_{d,s}}{100}\right) = .0611 \times 10^{\iota}\ ; \quad \iota = \frac{7.5T''_d}{237.3 + T''_d}$		(s31)
				$\left(\frac{\tau_{x,d}}{20}\right) = c'_{7,4}\left(\frac{K_{m,4}}{50,000}\right)\left(\frac{u_4}{5000} - \left(\frac{1}{5}\right)\frac{u_3}{1000}\right)$		(s32)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)		
				$\left(\frac{\tau_{y,d}}{20}\right) = c_{7,4}\left(\frac{K_{m,4}}{50,000}\right)\left(\frac{v_4}{5000} - \left(\frac{1}{5}\right)\frac{v_3}{1000}\right)$	(s33)
				$\frac{S_4}{2000} = \frac{\left(u_4^2 + v_4^2\right)^{1/2}}{2000}$	(s34)
				$\frac{Ri_4}{1} = \frac{50}{(2000)^2}\frac{\Lambda g}{\theta}\left(\frac{\theta_4 - \theta_d}{50}\right)\frac{1}{\left(\frac{S_4 + 300}{2000}\right)^2}$	(s35)
				$\frac{\beta}{1} = 1.003 - 1.163\,\frac{Ri_4}{1} - 9.627\,\frac{Ri_4^2}{1}$	(s36)
				$K_{m,4} = \frac{2000}{50,000}\,\frac{k^2(\Lambda)^{\beta}(1-\beta)z_o^{(\cdot\,-\beta)}}{\left(\frac{\Lambda}{z_o}\right)^{1-\beta} - 1}\left(\frac{S_4}{2000}\right)$	(s37)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	C. Forest, $\Lambda' \leq z \leq d-\Lambda$
3		35		$1440\left(\frac{u_3}{1000}\right) = \int \left[-5\left(\frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472}\right) + c_1\left(\frac{v_3}{1000}\right) + 5\ c_{2,3}\left(\frac{\tau_{x,d} - \tau_{x,23}}{20}\right) - \left(\frac{\alpha'_3 u_3 - \beta'_3 v_3}{.6944}\right) - c_{13} C'_{D,3}\left(\frac{u_3}{5000}\right)^2 \right]$ (s1f)
2		15		$1440\left(\frac{u_2}{1000}\right) = \int \left[-5\left(\frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472}\right) + c_1\left(\frac{v_2}{1000}\right) + 5\ c_{2,2}\left(\frac{\tau_{x,23} - \tau_{x,12}}{20}\right) - c'_{3,2}\left(\frac{\alpha'_1 u_1 - \beta'_1 v_1}{.6944}\right) - c'_{4,2}\left(\frac{\alpha'_3 u_3 - \beta'_3 v_3}{.6944}\right) - c_{13} C'_{D,2}\left(\frac{u_2}{5000}\right)^2 \right]$
1		1.5		$1440\left(\frac{u_1}{1000}\right) = \int \left[-5\left(\frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472}\right) + c_1\left(\frac{v_1}{1000}\right) + 5\ c_{2,1}\left(\frac{\tau_{x,12} - \tau_{x,o}}{20}\right) - \left(\frac{\alpha'_1 u_1 - \beta'_1 v_1}{.6944}\right) - c_{13}\ C'_{D,1}\left(\frac{u_1}{5000}\right)^2 \right]$

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
3		35		$1440\left(\frac{v_3}{1000}\right) = \int \left[-5\left(\frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472}\right) - c_1\left(\frac{u_3}{1000}\right) + 5\ c_{2,3}\left(\frac{\tau_{y,d} - \tau_{y,23}}{20}\right) - \left(\frac{\alpha_3' v_3 + \beta_3' u_3}{.6944}\right) - c_{13}\ C'_{D,3}\left(\frac{v_3}{5000}\right)^2\right]$
2		15		$1440\left(\frac{v_2}{1000}\right) = \int \left[-5\left(\frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472}\right) - c_1\left(\frac{u_2}{1000}\right) + 5\ c_{2,2}\left(\frac{\tau_{y,23} - \tau_{y,12}}{20}\right) - c'_{3,2}\left(\frac{\alpha_1' v_1 + \beta_1' u_1}{.6944}\right) - c'_{4,2}\left(\frac{\alpha_3' v_3 + \beta_3' u_3}{.6944}\right) - c_{13}\ C'_{D,2}\left(\frac{v_2}{5000}\right)^2\right]$ (s2f)
1		1.5		$1440\left(\frac{v_1}{1000}\right) = \int \left[-5\left(\frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472}\right) - c_1\left(\frac{u_1}{1000}\right) + 5\ c_{2,1}\left(\frac{\tau_{y,12} - \tau_{y,o}}{20}\right) - \left(\frac{\alpha_1' v_1 + \beta_1' u_1}{.6944}\right) - c_{13}\ C'_{D,1}\left(\frac{v_1}{5000}\right)^2\right]$

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
3		35		$1440\left(\frac{T_3}{50}\right) = \int \left[\frac{R}{.03472} - c_{5,3}\left(\frac{-q_{c,d-} - q_{c,23}}{.05}\right) - \left(\frac{u_3\left(\frac{\partial T}{\partial x}\right)_3 + v_3\left(\frac{\partial T}{\partial y}\right)_3}{.03472}\right)\right]$
2		15		$1440\left(\frac{T_2}{50}\right) = \int \left[\frac{R}{.03472} - c_{5,2}\left(\frac{q_{c,23} - q_{c,12}}{.05}\right) - c'_{3,2}\left(\frac{u_1\left(\frac{\partial T}{\partial x}\right)_1 + v_1\left(\frac{\partial T}{\partial y}\right)_1}{.03472}\right) - c'_{4,2}\left(\frac{u_3\left(\frac{\partial T}{\partial x}\right)_3 + v_3\left(\frac{\partial T}{\partial y}\right)_3}{.03472}\right)\right]$ (s3f)
1		1.5		$1440\left(\frac{T_1}{50}\right) = \int \left[\frac{R}{.03472} - c_{5,1}\left(\frac{q_{c,12} - q_{c,o}}{.05}\right) - \left(\frac{u_1\left(\frac{\partial T}{\partial x}\right)_1 + v_1\left(\frac{\partial T}{\partial y}\right)_1}{.03472}\right)\right]$
3		35		$1440\left(\frac{e_3}{100}\right) = \int \left[\frac{M}{.06944} - c_{6,3}\left(\frac{-q_{e,d-} - q_{e,23}}{.05}\right) - \left(\frac{u_3\left(\frac{\partial e}{\partial x}\right)_3 + v_3\left(\frac{\partial e}{\partial y}\right)_3}{.06944}\right)\right]$

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
2		15		$1440\left(\frac{e_2}{100}\right) = \int \left[\frac{M}{.06944} - c_{6,2}\left(\frac{q_{e,23} - q_{e,12}}{.05}\right) - c'_{3,2}\left(\frac{u_1\left(\frac{\partial e}{\partial x}\right)_1 + v_1\left(\frac{\partial e}{\partial y}\right)_1}{.06944}\right) - c'_{4,2}\left(\frac{u_3\left(\frac{\partial e}{\partial x}\right)_3 + v_3\left(\frac{\partial e}{\partial y}\right)_3}{.06944}\right)\right]$ (s4f)
1		1.5		$1440\left(\frac{e_1}{100}\right) = \int \left[\frac{M}{.06944} - c_{6,2}\left(\frac{q_{e,12} - q_{e,0}}{.05}\right) - \left(\frac{u_1\left(\frac{\partial e}{\partial x}\right)_1 + v_1\left(\frac{\partial e}{\partial y}\right)_1}{.06944}\right)\right]$
3	2		30	$\left(\frac{\tau_{x,23}}{20}\right) = c_{14,3}\left(\frac{u_3 - u_2}{1000}\right)\left(\frac{c'_{3,3} K_{m,1} + c'_{4,3} K_{m,4}}{50{,}000}\right)$
2	1		3	$\left(\frac{\tau_{x,12}}{20}\right) = c_{14,2}\left(\frac{u_2 - u_1}{1000}\right)\left(\frac{c'_{3,2} K_{m,1} + c'_{4,2} K_{m,4}}{50{,}000}\right)$ (s7f)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)		
3	2		30	$\left(\frac{\tau_{y,23}}{20}\right) = c_{14,3}\left(\frac{v_3 - v_2}{1000}\right)\left(\frac{c'_{3,3} K_{m,1} + c'_{4,3} K_{m,4}}{50{,}000}\right)$	(s8f)
2	1		3	$\left(\frac{\tau_{y,12}}{20}\right) = c_{14,2}\left(\frac{v_2 - v_1}{1000}\right)\left(\frac{c'_{3,2} K_{m,1} + c'_{4,2} K_{m,4}}{50{,}000}\right)$	
				$\left(\frac{u_{go}}{5000}\right) = -\frac{1440}{2\omega \sin \phi} \frac{g\left(\frac{\partial h}{\partial y}\right)_o}{3.472}$	(s9f)
				$\left(\frac{v_{go}}{5000}\right) = \frac{1440}{2\omega \sin \phi} \frac{g\left(\frac{\partial h}{\partial x}\right)_o}{3.472}$	(s10f)
3	2		30	$\left(\frac{q_{c,23}}{.05}\right) = -c_{15,3}\left(\frac{T_3 - T_2}{50}\right)\left(\frac{c'_{3,3} K_{h,1} + c'_{4,3} K_{h,4}}{50{,}000}\right)$	(s11f)
2	1		3	$\left(\frac{q_{c,12}}{.05}\right) = -c_{15,2}\left(\frac{T_2 - T_1}{50}\right)\left(\frac{c'_{3,2} K_{h,1} + c'_{4,2} K_{h,4}}{50{,}000}\right)$	

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)		
3	2		30	$\left(\frac{q_{e,23}}{.05}\right) = c_{16,3}\left[c_{10,3}\left(\frac{e_3}{100}\right) - \frac{e_3}{100}\right]\left(\frac{c'_{3,3}\,K_{v,1} + c'_{4,3}\,K_{v,4}}{50{,}000}\right)$	(s12f)
2	1		3	$\left(\frac{q_{e,12}}{.05}\right) = c_{16,2}\left[c_{10,2}\left(\frac{e_2}{100}\right) - \frac{e_1}{100}\right]\left(\frac{c'_{3,2}\,K_{v,1} + c'_{4,2}\,K_{v,4}}{50{,}000}\right)$	
3	2		30	$K_{m,23} = c'_{3,3}K_{m,1} + c'_{4,3}K_{m,4}$	(s17f)
2	1		3	$K_{m,12} = c'_{3,2}K_{m,1} + c'_{4,2}K_{m,4}$	
j	i	z_j (m)	z_{ij} (m)	D. Forest surface section, $z = 0$	
0		0		$\frac{R_N}{.05} = \left(\frac{q_{c,o}}{.05}\right) + \left(\frac{q_{e,o}}{.05}\right) + \left(\frac{q_{s,o}}{.05}\right)$	(s18f)
				$\frac{R_N}{.05} = \left(\frac{I}{.05}\right) \chi\,(1 - J)\psi e^{-N_{F_c}} \cos\zeta + \left(\frac{\sigma T^4_{\Lambda'}}{.05}\right)\left(m + 10n\sqrt{\frac{e'_{\Lambda'}}{100}}\right) - \varepsilon\left(\frac{T^4_o}{.05}\right)$	(s19f)
				$\frac{\cos\zeta}{1} = \frac{\sin\phi}{1}\,\frac{\sin\delta}{1} + \frac{\cos\phi}{1}\,\frac{\cos\delta}{1}\,\frac{\cos(15[t-12])}{1}$	(s21f)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)		
				$\frac{e_o}{100} = \frac{e_{o,s}}{100} - \frac{.05}{s_o}\left(\frac{q_{e,o}}{.05}\right) \quad ; \quad q_{e,o} > 0$	(s24f)
				$\frac{e_o}{100} = \frac{e_{o,s}}{100} \quad ; \quad q_{e,o} \leq 0$	(s25f)
				$\frac{T'_o}{50} = \frac{T_o}{50} - 5\left(\frac{G}{5000}\right)\left(\frac{q_{s,o}}{.05}\right)$	(s26f)
				$\frac{q_{e,o}}{.05} = \frac{(1000)\rho aL}{.05 p_o}\left(\frac{D_1}{10}\right)\left(\frac{e_o - e_1}{100}\right)$	(s27f)
				$\frac{q_{c,o}}{.05} = \frac{(500)\rho c_p}{.05}\left(\frac{D_1}{10}\right)\left(\frac{T_o - T_1}{50}\right)$	(s28f)
				$1440\left(\frac{T'_o}{50}\right) = \int \left[\frac{(1440)(.05)}{50}\, 2\left(\frac{\pi}{P}\right)^{1/2} \frac{1}{\sqrt{\lambda\mu}}\left(\frac{q_{s,o}}{50}\right) - \frac{2\pi}{P}\left(\frac{T'_o - T'_{\bar{s}}}{50}\right)\right]$	(s29f)
				$\frac{\tau_{x,o}}{20} = \frac{(10)(1000)}{20}\,\rho\left(\frac{D_1}{10}\right)\left(\frac{u_1}{1000}\right)$	(s30f)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)		
				$\dfrac{\tau_{y,o}}{20} = \dfrac{(10)(1000)}{20}\,\rho\left(\dfrac{D_1}{10}\right)\left(\dfrac{v_1}{1000}\right)$	(s31f)
				$\dfrac{e_{o,s}}{100} = 0.0611 \times 10^{\iota} \quad ; \quad \iota = \dfrac{7.5T''_o}{237.3 + T''_o}$	(s32f)
				$\dfrac{S_1}{1000} = \dfrac{\left(u_1^2 + v_1^2\right)^{1/2}}{1000}$	(s33f)
				$\dfrac{Ri_1}{1} = \dfrac{50}{(1000)^2}\,\dfrac{\Lambda' g}{\theta}\left(\dfrac{\theta_1 - \theta_o}{50}\right)\dfrac{1}{\left(\dfrac{S_1 + 300}{1000}\right)^2}$	(s34f)
				$\dfrac{\beta}{1} = 1.003 - 1.163\,\dfrac{Ri_1}{1} - 9.627\,\dfrac{Ri_1^2}{1}$	(s35f)
				$\dfrac{D_1}{10} = 100\left[\dfrac{k(1-\beta)}{\left(\dfrac{\Lambda'}{z_o}\right)^{1-\beta} - 1}\right]^2\left(\dfrac{S_1}{1000}\right)$	(s36f)

Table 2. Continued

j	i	z_j (m)	z_{ij} (m)	
				$\frac{K_{m,1}}{50,000} = \frac{1000}{50,000} \frac{k^2(\Lambda')^{\beta}(1-\beta)z_o^{(1-\beta)}}{\left[\left(\frac{\Lambda'}{z_o}\right)^{1-\beta} - 1\right]} \left(\frac{S_1}{1000}\right)$ (s37f)

at the surface and at the top of the canopy, are given for these very special regions in the sections indicated by B and D, (equations s19 - s37 and s18f - s37f respectively).

The specific levels and layer depths used in a simulation do not enter into the scaled equations except in the coefficients which are combinations of geometric dimensions, non-time-dependent physical variables and factors required to maintain algebraic correctness when scaling the meteorological parameters. The depth of forest, d, to be used in the intial tests is 40 meters and the depths of the surface layer (Λ') and the air-canopy layer (2Λ) are 1.5 and 10 meters, respectively. The mathematical forms of the coefficients and the numerical values to be used in the initial test solutions are given in Table 3.

The wind components have been scaled for maxima of 50 m/sec above the canopy. Observations indicate that the winds in the forest are quite light and 50 m/sec would probably be a gross over-estimate of the maximum values likely to be attained. Therefore, the wind components in the forest have been scaled for 10 m/sec. The temperature is scaled for 50°C and the vapor pressure for 100 mb both above and within the forest. Thus, the principal computer variables for which solutions are sought become u/5000, v/5000 in the free air, u/1000, v/1000 in the forest, T/50 and e/100 both in the free air and in the forest. The eddy-stresses have been scaled to 20 dynes per cm^2, the sensible and latent heat fluxes to .05 cal/cm^2 sec. The scale

Table 3. Form and magnitude of the coefficients in the scaled format of the equations for the forested boundary layer.

Coefficient	j = 1	2	3	4	5	6	7
$b'_{1,j} = \frac{K_{m,j,1}}{K_{m,4}}$, $4 \le j \le 7$ (eqn. a 16)	—	—	—	1	1.9809	10.7701	23.2112
$c_1 = 1440\ (2\omega)\ \sin\varphi$	.2101 $\sin\varphi$						
$c_{2,j} = \frac{1440}{5000}\left(\frac{20}{\rho\ \Delta z_j}\right)$; $c'_{2,7} = c_{2,7}\left(\frac{K_{m,78}}{K_{m,67}} - 1\right)$	16.0000	1.7778	4.8000	4.8000	0.9600	0.4800	0.1344
$c_{3,j} = \left(1 - c_{4,j}\right)$; $c'_{3,j} = \left(1 - c'_{3,j}\right)$	1.0	.5970	0.0	1.0	0.8537	0.4878	0.0
$c_{4,j} = \frac{z_j - z_4}{z_7 - z_4}$, $7 \le j \le 4$; $c'_{4,j} = \frac{z_j - z_1}{z_3 - z_1}$, $3 \le j \le 1$	0.0	.4030	1.0	0.0	0.1463	0.5122	1.0
$c_{5,j} = \frac{1440}{50}\left(\frac{.05}{\rho C_p \Delta z_j}\right)$; $c'_{5,7} = c_{5,7}\left(\frac{K_{m,78}}{K_{m,67}} - 1\right)$	1.6667	1.8519	5.000	5.0000	1.0000	0.5000	0.1402
$c_{6,j} = \frac{1440}{100}\left(\frac{.05 p_j}{\rho a L \Delta z_j}\right)$; $c'_{6,7} = c_{6,7}\left(\frac{K_{m,78}}{K_{m,67}} - 1\right)$	5.493	0.610	1.647	1.6394	0.3267	0.1619	0.04486
$c_{7,j} = \frac{(50{,}000)(5000)\rho}{20(z_j - z_1)}\left(\frac{K_{m,j,1}}{K_{m,4}}\right)$; $j > 4$	—	—	—	—	9.9047	21.5402	34.8168
$c'_{7,4} = \frac{(50{,}000)(5000)\rho}{20 z_d (\ln z_4 - \ln z_\delta)}$	—	—	—	14.922	—	—	—
$c_{8,j} = \frac{(50{,}000)(50)\rho C_p}{.05(z_j - z_1)}\left(\frac{K_{m,j,1}}{K_{m,4}}\right)$; $j > 4$	—	—	—	—	9.5064	20.6776	33.4221
$c'_{8,j} = \frac{(50{,}000)(50)\rho C_p}{.05\lvert z_j - z_d \rvert}$, $j = 4$	—	—	—	28.8000	—	—	—
$c_{8,j} = \frac{(50{,}000)(100)\rho a L}{.05\ p_j (z_j - z_1)}\left(\frac{K_{m,j,1}}{K_{m,4}}\right)$, $j > 4$	—	—	—	—	29.0952	63.8472	104.440

Table 3. Continued

Coefficient	1	2	3	4	5	6	7
$c'_{9,j} = \frac{(50,000)(100)\rho a L}{.05\ p_d \lvert z_j - z_d \rvert}$; $j = 4$	—	—	—	87.381	—	—	—
$c_{10,j} = \frac{p_j}{p_1}$	1.0000	0.99998	0.99997	—	0.9965	0.9912	0.9882
$\frac{g}{.8}\ c_{11,j}$	0	0	0	0	.1163	.3266	.4286
$\frac{g}{.8}\ c_{12,j}$	0	0	0	0	.00918	.1124	.4286
$c_{13} = \frac{1}{2}(1440)(5000)^2$	$18\text{x}10^9$	$18\text{x}10^9$	$18\text{x}10^9$	$18\text{x}10^9$	$18\text{x}10^9$	$18\text{x}10^9$	$18\text{x}10^9$
$c_{14,j} = \frac{(5000)(1000)\rho}{(20)(z_j - z_1)}$; $1 < j \le 3$	—	.2222	.1500	—	—	—	—
$c_{15,j} = \frac{(50,000)(50)\rho C_p}{.05\ (z_j - z_1)}$; $1 < j \le 3$	—	10.6667	7.2000	—	—	—	—
$c_{16,j} = \frac{(50,000)(100)\rho a L}{.05\ p_j (z_j - z_1)}$; $1 < j \le 3$	—	32.3624	21.8451	—	—	—	—

factors employed for the other variables will be covered in the course of the discussion of the individual terms of the scaled equations.

A one-to-one correspondence exists between the general and scaled formats of the same number. However, it is not always clear how the one follows from the other, partly because of the level and layer multiplicity but largely because of the substitutions from the defining relationships and certain approximations which simplify the solution. Consequently, each of the terms in the equations for the basic meteorological parameters are discussed in some detail below.

A. The Wind Components (equations s1, s2, s1f, s2f)

The forms of the equations for the free air and the forest atmospheres are essentially the same except for the addition of a drag force in those for the forest. It is fairly simple to follow the transformation from the defining mathematical expression to the general analog format except for the advection terms. These have been re-expressed, partially, in terms of derivatives obtainable from kinematic analyses. The factor of 5 appearing with some of the terms in the forest equations (s1f, s2f) enters because the coefficient corrects for a wind scale factor of 5000 cm/sec whereas the winds in the forest are scaled for 1000 cm/sec. A term-by-term discussion of the scaled east-west wind expressions follows.

1. The Contour Gradient

The contour gradient forces, $g\frac{\partial h}{\partial x}$, $g\frac{\partial h}{\partial y}$ are effectively scaled by the time and velocity scale factors and the need to maintain algebraic correctness. The rather peculiar scale factor of 3.472 cm/sec^2 is the ratio of the velocity and time scales in the free air.

The contour gradient at any level is obtained through a "buildup" from the surface value in successive steps from level 1 through level 7, by the use of equations (a17) and (a18). These equations stem from an elementary re-expression of the horizontal contour gradient at any level as that at a lower one plus the gradient of the thickness between the pressure surfaces passing through the two levels. The familiar hypsometric equation relates thickness between two pressure surfaces to the mean temperature in the layer. The temperature gradient term on the right hand side of (a17), (a18) may be viewed as a pseudo-correction to be applied to the horizontal contour gradient at a lower level to obtain the horizontal contour gradient at the upper level. Through buildup from the surface, only the surface contour gradient and the horizontal temperature gradients are required as input.

It has been assumed that the horizontal temperature gradient term is small in the forest so that up through the 4th level the contour gradient is given by the surface value (equations a1f, a2f, j=4 in a1 and a2). For all levels above

4 the contour gradient is expressed as the surface contour gradient plus a correction term which is computed from equation (s17). The value of the surface contour gradient is generated on the analog computer as a linear interpolation in time between the observed contour gradient at the start of the forecast period and a predicted contour pattern at the end of the forecast period, Δt, (equation s18). The initial and final contour gradients are scaled to 100 m/100 km for contour gradients expressed in the same units.

The horizontal temperature gradients are routinely available only at the surface and at 850 mb. The temperature gradients at the lowest and highest levels in the forest and the lowest and highest levels in the free air will be obtained by linear interpolation between the surface and 850 mb levels. These will be used as input for the solution and temperature gradients at all other levels will be obtained by linear interpolation between these. Thus, the correction term to the contour gradient (equation a17) is expressed as a function of the horizontal temperature gradients at the lowest and highest levels (levels 4 and 7 in our initial forest model). Coefficients c_{11} and c_{12} are not simple linear geometric ratios but rather the ~~sum~~ of products of the ratio $\frac{\Delta h}{T}$ and linear interpolation factors. They also contain conversion factors which permit the temperature gradients to be expressed in degrees C/100 km. The thickness, Δh, is approximately

equal to the height difference between the two levels. The temperature is the mean for the column between levels z_1 and z_j but in practice a constant temperature of 298°C is used. The percentage error involved in these two approximations is very small. The correction term is scaled over a value of 4.34 cm/sec^2 rather than the 3.472 used for the surface contour gradient. Previous experience has shown that the term was underscaled if the latter was used. For the initial test solutions the assumption will be made that the horizontal temperature gradient does not change significantly over the forecast period.

2. Coriolis Force

The coriolis force (fu, fv) is carried over directly into the analog format. The computer variable, rather than the physical variable, is used in the scaled format. This takes care of the velocity scale factor. The time scale factor is included in the coefficient c_1, which also incorporates the coriolis parameter, f, a problem parameter.

3. Eddy-stress Terms

The eddy-stress terms in the equations of motion are approximated by finite difference methods, using the values at the bottom and top of the layer containing the particular level. The assumption is made implicitly that the stress varies linearly through the layer. The eddy-stress terms are computed at layer interfaces, as indicated by the double subscript index (e.g., equation s7, s8). The quantity $\tau_{x,56}$ is the x-

component of the shearing stress at the interface of the layers containing levels 5 and 6 (a height of 100 m in our particular forest model). Similarly $\tau_{x,67}$ is the x-component of the stress at the interface of layers 6 and 7 (200 m in our model). The coefficient c_2 incorporates the density, the thickness of the layer and the scale factors for algebraic correctness. Since winds are not computed for any levels above 7, the stress at the top of the layer containing level 7 cannot be calculated directly. The assumption is made that the vertical gradients of the wind components at the top of this upper layer in the free air is the same as it is at the bottom. From equation (a7), (a8) the ratio of the horizontal wind stress at the top and the bottom of the layer then becomes equal to the ratio of the momentum exchange coefficients at the top and the bottom of the layer, that is,

$$\frac{\tau_{x,78}}{\tau_{x,67}} = \frac{K_{m,78}}{K_{m,67}} \; ; \; \frac{\tau_{y,78}}{\tau_{y,67}} = \frac{K_{m,78}}{K_{m,67}}$$

This assumption permits τ_{78} to be expressed in terms of τ_{67} in the first equations of the sets (s1) and (s2). The factor which this substitution introduces is incorporated into the coefficient $c_{2,7}$.

The horizontal wind stress for the atmospheric levels is calculated by finite difference methods (equations a7, a8, a7f, a8f) assuming that the wind components vary linearly between two successive levels, except in the free air-canopy and forest

surface layers (a32, a33, a30f, a31f). Computation of the stress at the top of the canopy is based on the assumption that the wind components vary logarithmically between the level just below and that just above (a32, a33). The surface stress is determined (a30f, a31f) using an integral momentum exchange coefficient between the surface and the first level.

The momentum exchange coefficient at the first level above the ground and at the first level above the top of the canopy (equations a37f, a37) are derived for wind profiles given by Deacon's β-equation and constant stress in surface layer ($0 < z \leq \Lambda'$) and in the upper air-canopy layer ($d \leq z \leq d + \Lambda$). The values of the stresses and of the parameter, β, are independently determined for the two levels. For the initial test simulation the exchange coefficient is assumed to be constant in the free air-canopy section ($d - \Lambda \leq z \leq d + \Lambda$) and to vary linearly between levels 1 and 3 in the forest (equation a17f). In the free air above the canopy the exchange coefficient is assumed to vary in accordance with the empirical relationship (a15, a16) developed during the earlier boundary-layer simulations. This assumed vertical structure permits the stress at all other layer interfaces to be expressed in terms of the exchange coefficient at the 4th level (equations s7, s8, s32, s33) or as a combination of the exchange coefficients at the 1st and 4th levels (s7f, s8f) with a considerable saving in necessary equipment.

The exchange coefficients have been scaled for 50,000 cm^2/sec. The coefficient c_7 includes the scale factors required to maintain algebraic accuracy, the depth of the layer separating the two wind measurements, and the density, as well as the ratio, b'_{ij}, between the exchange coefficients at the height in question and that at the height of level 4. The coefficient c_{14} in the stress equations for the forest incorporates the depth between the two wind measurements and the density.

4. Horizontal Advection of Momentum

The horizontal advection of momentum in the equations of motion have been re-expressed in the transformation from the mathematical to the analog format so that the horizontal gradients of the wind components can be estimated from kinematic analyses. The advection terms become:

$$u\,(du/dx) + v\,(du/dy) = \alpha' u - \beta' v$$

$$\text{and } u\,(dv/dx) + u\,(dv/dy) = \alpha' v + \beta' u$$

where α' is the gradient of the wind speed along the stream line and β' is the ratio of the wind speed to the radius of curvature of the stream line.

The values of α' and β' are routinely available only at the surface and the 850 mb level. Following the method outlined above for the temperature gradients, the values of α' and β' will be determined at the lowest and highest levels in the forest (levels 1 and 3) and in the free air above the canopy (levels 4 and 7) by linear interpolation. These

will be used as input quantities for the simulation. The products, $\alpha' u$, $\beta' v$, $\alpha' v$, $\beta' u$ and the sum and difference given above are formed in the simulation using the computer generated values of u and v at levels 1, 3, 4, and 7, and the input α', β'. At all other levels, the advective term is obtained by linear interpolation of the advection calculated for these four levels. Thus the advective term for level 6 appears as a linear combination of the values at levels 4 and 7 with the coefficients, c_3 and c_4, representing simple linear interpolation factors. Similarly the advective term at level 2 appears as a linear combination of the advective terms at levels 1 and 3. In the free air the advective terms are scaled for 3.472 cm/sec^2, for the same reasons that were given in the discussion of the contour gradient. The scaling for the advective terms in the forest (equations s1f and s2f) is .6944, down by a factor of five because of the lighter winds.

5. The Drag Force

The analog transform for the drag force in the equations of motion in the forest (s1f, s2f) is straightforward. The free density and local drag coefficient have been combined into a single coefficient, C'_D, which is now a characteristic of the forest, and which will vary through the depth of the forest. The drag force term has been scaled for 1000 cm/sec^2 (equations s1f, s2f), but it is

anticipated that this will need to be changed following the determination of the magnitude of C'_D. The coefficient c_{13} is simply a combination of scale parameters required to keep the equations algebraically correct.

Equations (a9) and (a10) for determination of the geostrophic wind utilize the surface contour gradient acceleration term generated by equation (s18).

B. Air Temperature (equations s3, s3f)

The transformation of the expression for temperature (equations 3, 3f) to the scaled analog format (s3, s3f) is similar to that for the wind component equations.

1. Heat Source Term, R

The sensible heat source term which appears both in the free air and in the forest has been scaled over the value .03472, the ratio of the temperature scale factor to the time scale factor. Above the canopy this term represents primarily radiational cooling arising from the water vapor in the atmosphere. In the forest this term is more complicated since not only the atmosphere but the foliage acts as a heat source (sink). The manner in which the forest term will be handled has not been settled and is under investigation. Above the canopy the approach will be similar to that which has been employed in previous simulations on the GPAC.

2. Convective Heat Flux

The convective heat flux terms are analogous to the stress

terms in the momentum equations and analog forms for these terms in the temperature equations (a3 and a3f) are very similar to the analog forms of the stress terms. Since the temperature is not computed for levels above 7, the flux at the upper boundary of the top layer is expressed as a function of that at the lower boundary by using the same argument that was used for the horizontal stress at the same boundary. That is, the vertical temperature gradient is assumed to be the same at the bottom and top of the uppermost layer in the free air section so that, from equation (a9), the ratio of the flux at the top of the layer to the flux at the bottom of the layer is equal to the ratio of the heat exchange coefficients at the top and bottom of the layer. Thus the calculation of the temperature at level 7 (equation s9) involves only the convective flux at the interface of levels 6 and 7.

The convective heat fluxes are obtained from equations (s9) and (s11f), under the implicit assumption that the temperature varies linearly between two successive levels. Since the heat exchange coefficient, K_h, is assumed equal to the momentum exchange coefficient, the value at any level above the forest can be expressed as a function of the exchange coefficient at level 4 by equations (a15) and (a16). In the forest the exchange coefficient is given as a function of those at the first and fourth levels by using the relationship given in equation (37).

Since the vertical temperature gradient just above the canopy may be different from that in the upper portion of the canopy the upward convective flux at the air-canopy interface is calculated separately from the downward flux from the same level. The former is based on the change of temperature in the small layer just above the interface (equation s25) and the latter on the change of temperature in the small layer just below (equation s26).

3. Horizontal Temperature Advection

As might be expected the temperature advection terms are handled in exactly the same manner as the wind advection terms. That is, the temperature gradients, $\partial T/\partial x$ and $\partial T/\partial y$, like α and β, are obtained at levels 1, 3, 4, and 7, by linear interpolation between surface and 850 mb and only these are used as input. From this input, $[u(\partial T/\partial x)$ and $v(\partial T/\partial y)]$ at the same levels are computed and linear interpolation is employed to obtain the values at the other levels.

The values of the horizontal temperature gradients must be expressed in units of deg/cm for this equation to be used directly since the coefficients c_3 and c_4 are simply interpolation factors. For the initial simulation the horizontal temperature gradient will be treated as invariant in time.

C. Vapor Pressure

The defining equations for the atmospheric vapor pressure

(equations 4 and 4f) are very similar to those for air temperature (3 and 3f). Not too surprisingly the analog and scaled forms are also very similar to those for temperature and were obtained in a manner almost identical to that described in section II B, above.

The vapor source term, M, in the forest (s3f) includes both evapo-transpiration of the vegetation and condensation (evaporation) in the atmosphere. For the initial simulation the latter will be assumed to be zero in the free air above the forest, i.e., none will be permitted.

In the transformation from mathematical (equations 10 and 12f) to analog format, the evaporative heat flux has been re-expressed in terms of the vapor pressure utilizing the relationship given in equation (11). This substitution introduced the pressure at each simulation level which, under the hydrostatic assumption and the assumption of constant density, are determined from equation (a5). As in the case of the stresses and convective fluxes the solution of the evaporative fluxes is based on finite differencing techniques. In addition there has been some algebraic manipulation in arriving at equations (s10) and (s12f) so that only one of the factors in the difference on the right hand side contains a multiplier and the pressure at only one level appears in the equation explicitly. Beyond this the evaporative heat fluxes are obtained in a manner similar to that described for the convective fluxes not only in the free air and forest sections but also at the air-canopy interface.

III. Diffusion experiments in the Panamanian Forest

Smoke releases were made in the forest of the Panama Canal Zone during the last week of August. The chief purpose of these releases was to familiarize contract personnel with the air flow in a tropical forest. Thus the tests were qualitative in nature and observations were primarily visual or photographic. A concerted effort was made to obtain some idea as to the influence of terrain, tree density, time of day, cloudiness, local clearings, and surface brush.

Several sites having different terrain, tree types and foliage characteristics were selected for the tests. Although the density of the forest at the sites varied considerably, the depth of the forest, i.e., the height of the top of the canopy, was fairly uniform around 100 to 120 ft. Smoke pots and grenades provided the tracer material. The grenades provided smoke releases in ravines, streams, slopes, and generally inaccessible locations. They were nearly always used in conjunction with smoke pots located at more level locations. All release points were on the ground.

Very little supporting meteorological data are available. Three tests, at one hour intervals on a single day, were made at the Albrook Data Base Site. For these tests, recorded measurements are available at 5 minute intervals for the wind direction and speed at the 46 m level (about 16 m above the forest canopy)

and for temperature and dewpoint at a number of levels on the tower. The wind measurements in particular are valuable since they provide information about the amount of turning that occurs through the canopy. For all but two of the other tests, tethered pilot balloons were used to estimate the direction of the wind above the canopy. This method was not very satisfactory.

Our limited observations are briefly summarized below.

1. There was unmistakable, and frequently pronounced, horizontal transport of the materials in the forest and, except for an initial vertical motion, this was the dominant transport.

2. There was spreading of the plume, indicating diffusion of material around the mean direction of the flow. The behavior of the smoke was, generally, not very different from that of stack plumes with moderate flue temperature at more open sites.

3. The horizontal transport appeared to be nearly constant in direction from about four meters above ground to at least sixty to seventy percent of the height of the forest.

4. At Albrook the direction in which the smoke plume moved through the forest was within 30° of the wind direction 16 m above the forest. It was always to the left of the wind, suggesting clockwise turning (veering) of the wind with height through the canopy. In many of the other tests also, the

transport in the forest appeared to be 20 to 45 degrees to the left of the wind above the forest. However, the tethered balloon estimates of the free air wind are not very accurate.

5. Although the horizontal transport tended to maintain a mean direction, oscillations in direction, with periods of a few minutes, were noticed in nearly every test. The oscillation usually had an amplitude of about ± 30° of the mean transport direction, but at least once it was more pronounced (directional change of 130-150 degrees) and also of longer period (eight to ten minutes). The Albrook observations 16 m above the top of the canopy indicated variations in wind direction of the same magnitude as that observed for the smoke plume in the forest. Because of the relatively long time between observations (5 minutes), it is difficult to ascertain the period of the directional deviation.

6. At only one site was smoke clearly seen above the canopy. This occurred in the thinnest of the forest sites in early afternoon. There may, however, have been some movement up through the canopy in other tests where poor viewing conditions made it difficult to detect the smoke in the free air.

7. Diurnal changes could be checked on only the one day when three runs were made at hourly intervals between 0930 and 1130. The horizontal transport was predominantly from the southwest in the first test, from the east on the second and

principally from the west in the third. These tests were made at the Albrook Tower Site and the recorded winds 16 m above the forest show the same longer period variation.

8. Terrain appears to affect the horizontal transport very little. The smoke from grenades thrown into stream beds and gullies tended to move up and out and take on the motion of the general horizontal transport as indicated by the smoke from releases at more level sites in the vicinity. Similarly smoke grenades thrown up on to slopes tended to drift in the general direction of the horizontal transport and did not tend to flow either up slope or down slope unless they coincided with the mean direction. Small hills or knolls, however, did appear to cause a decrease in wind speed in the lowest 5 m immediately downwind.

9. Local clearings and roads seemed to have little effect in the general transport of the smoke. The plume from forest releases were observed to cross clearings and wide roads and to re-enter the forest on the other side. However, the cross-wind diffusion of material was enhanced in the clearings and particularly at wide roads.

GLOSSARY

A	characteristic tree coverage	(cm^{-1})
a	ratio of molecular weight of water to molecular weight of dry air	(non-dimensional)
C_D	local drag coefficient	(non-dimensional)
C_D'	forest drag coefficient ($C_D' = AC_D$)	(cm^{-1})
C_p	specific heat of air at constant pressure	(cal/gm deg)
d	height of the effective top of the canopy	(cm)
$D_{\Lambda'}$	integral exchange coefficient for momentum between surface and height Λ'	(cm/sec)
e	mean vapor pressure	(mb)
e'	representative vapor pressure	(mb)
$e_{o,s}$	surface saturation vapor pressure	(mb)
$e_{d,s}$	saturation vapor pressure at the temperature of the canopy top	(mb)
F_c	cloud factor for insolation	(non-dimensional)
FCG	forecast contour gradient	(m/100 km)
(FCG)	angle made by the forecast contour gradient with the y-axis	
f	Coriolis parameter	(rad/sec)
F_x, F_y	components of drag force due to trees and foliage	(cm/sec^2)
G	thermal resistance of surface litter	(cm^2 sec deg/cal)
g	acceleration due to gravity	(cm/sec^2)
H	hour angle (zero for local apparent noon)	(rad)
h	height of a constant pressure surface	(cm)
I	mean solar constant	(cal/cm^2 sec)

ICG	initial contour gradient	(m/100 km)
(ICG)	angle made by the initial contour gradient vector with the y-axis	
i,j,k	indices	
J	albedo	(non-dimensional)
K_h	exchange coefficient for heat	(cm^2/sec)
K_m	exchange coefficient for momentum	(cm^2/sec)
K_v	exchange coefficient for water vapor	(cm^2/sec)
k	.40 (Von Kárman's constant)	(non-dimensional)
L	latent heat of vaporization of water	(cal/gm)
L_N	net longwave radiation	(cal/cm^2 sec)
m	empirical radiation factor	(non-dimensional)
n	empirical radiation factor	($mb^{-\frac{1}{2}}$)
M	moisture source term for forest	(mb/sec)
N	turbidity	(non-dimensional)
P	86,400 (diurnal period)	(sec)
p	atmospheric pressure	(mb)
Q	energy addition per unit mass from non-adiabatic processes	(cal/gm)
q	specific humidity	(non-dimensional)
q_c	convective heat flux, positive upward	(cal/cm^2 sec)
$q_{c,d+}$	convective heat flux in air layer just above canopy, positive upward	(cal/cm^2 sec)
$q_{c,d-}$	convective heat flux in canopy just below the level d, positive downward	(cal/cm^2 sec)
q_e	evaporative heat flux, positive upward	(cal/cm^2 sec)

$q_{e,d+}$	evaporative heat flux in air layer just above canopy, positive upward	(cal/cm^2 sec)
$q_{e,d-}$	evaporative heat flux in canopy just below the level d, positive downward	(cal/cm^2 sec)
q_s	soil heat flux, positive downward	(cal/cm^2 sec)
R	radiational cooling or warming	(deg/sec)
R_a	gas content for dry air	(cm^2/sec^2 deg)
R_N	net radiation	(cal/cm^2 sec)
S	wind speed	(cm/sec)
S_N	net shortwave radiation	(cal/cm^2 sec)
s_o	surface moistness	(cal/cm^2 sec mb)
T	mean temperature of air	(deg C.)
T'	mean soil temperature	(deg C.)
T'_r	representative soil temperature	(deg C.)
T''	dewpoint temperature	(deg C.)
t	time	(sec)
u	mean east-west component of wind	(cm/sec)
v	mean north-south component of wind	(cm/sec)
u_g, v_g	geostrophic wind components	(cm/sec)
x	east-west coordinate, positive eastward	(cm)
y	north-south coordinate, positive northward	(cm)
Z	105,000, top of boundary layer	(cm)
z	vertical coordinate, positive upward	(cm)
z_o	surface roughness length	(cm)
zero	as a subscript indicates value at $z = 0$, excepting s_o and z_o	

α'	gradient of wind along streamline	(sec^{-1})
β	stability parameter in the Deacon profile	(non-dimensional)
β'	ratio of wind speed to radius of curvature of streamline	(sec^{-1})
δ	solar declination	(rad)
Δh	vertical interval between adjacent simulator levels	(cm)
Δt	total forecast period	(sec)
ϵ	emissivity	(non-dimensional)
ζ	solar zenith angle	(rad)
θ	mean potential temperature	(deg C.)
Λ	½ depth of air-canopy layer	(cm)
Λ'	depth of forest surface layer	(cm)
λ	volumetric heat capacity of soil	($cal/cm^3 deg$)
μ	thermal conductivity of soil	(cal/cm sec deg)
ξ	moisture parameter for the canopy	($cal/cm^2 sec\ mb$)
π	3.14. . . .	(non-dimensional)
ρ	air density	(gm/cm^3)
σ	5.67×10^{-5} Stefan-Boltzmann constant	($ergs/cm^2 sec\ deg^4$)
τ_x	component of τ in x direction	($dynes/cm^2$)
τ_y	component of τ in y direction	($dynes/cm^2$)
φ	latitude	(deg)
χ	forest transmissivity	(non-dimensional)
ψ	solar distance factor	(non-dimensional)
ω	7.3×10^{-5} (angular velocity of earth's rotation)	(rad/sec)

APPENDIX A

A. Free Air Section

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - g \frac{\partial h}{\partial x} + fv + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} \tag{1}$$

$$\frac{\partial v}{\partial t} = -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - g \frac{\partial h}{\partial y} - fu + \frac{1}{\rho} \frac{\partial \tau_y}{\partial z} \tag{2}$$

$$\frac{\partial T}{\partial t} = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - \frac{1}{\rho C_p} \frac{\partial q_c}{\partial z} + R \tag{3}$$

$$\frac{\partial e}{\partial t} = -u \frac{\partial e}{\partial x} - v \frac{\partial e}{\partial y} - \frac{p}{\rho a L} \frac{\partial q_e}{\partial z} \tag{4}$$

$$p = p_o - \rho g z \tag{5}$$

$$f = 2\omega \sin \phi \tag{6}$$

$$\tau_x = \rho K_m \frac{\partial u}{\partial z} \tag{7}$$

$$\tau_y = \rho K_m \frac{\partial v}{\partial z} \tag{8}$$

$$q_c = - \rho C_p K_h \frac{\partial T}{\partial z} \tag{9}$$

$$q_e = - \rho L K_v \frac{\partial q}{\partial z} \tag{10}$$

$$q = \frac{ae}{p} \tag{11}$$

$$R = \frac{1}{C_p} \frac{dQ}{dt} \tag{12}$$

$$\rho = \left(\frac{p}{R_a T}\right)_{t=0} \tag{13}$$

$$K_m = K_h = K_v \tag{14}$$

$$K_m = b\left(\frac{z-d}{Z}\right)\left(1-\frac{z-d}{Z}\right)^2 \quad ;(d+\Lambda) < z < (Z+d) \tag{15}$$

$$b = \left(\frac{Z}{\Lambda}\right)\left(\frac{Z}{Z-\Lambda}\right)^2 K_{m,d+\Lambda} \tag{16}$$

$$\left(\frac{\partial h}{\partial x}\right)_{j+1} = \left(\frac{\partial h}{\partial x}\right)_j + \frac{\Delta h_{m,m+1}}{\bar{T}}\left(\frac{\partial \bar{T}}{\partial x}\right)_{j,j+1} \tag{17}$$

$$\left(\frac{\partial h}{\partial y}\right)_{j+1} = \left(\frac{\partial h}{\partial y}\right)_j + \frac{\Delta h_{m,m+1}}{\bar{T}}\left(\frac{\partial \bar{T}}{\partial y}\right)_{j,j+1} \tag{18}$$

B. Free Air-Canopy Section

$$R_N = (q_{c,d+} + q_{e,d+}) + (q_{c,d-} + q_{e,d-}) \tag{19}$$

$$R_N = S_N + L_N \tag{20}$$

$$S_N = (1-J)I\psi\cos\zeta\, e^{-NF_c} \tag{21}$$

$$\cos\zeta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos H \tag{22}$$

$$H = 15(t-12) \tag{23}$$

$$L_N = \sigma T^4_{d+\Lambda}\,(m + n\sqrt{e'_{d+\Lambda}}) - \varepsilon\sigma T^4_d \tag{24}$$

$$q_{c,d+} = \rho\, C_p\, K_{m,d}(T_d - T_{d+\Lambda})/\Lambda \quad \text{(positive up)} \tag{25}$$

$$q_{c,d-} = \rho\, C_p\, K_{m,d}(T_d - T_{d-\Lambda})/\Lambda \quad \text{(positive down)} \tag{26}$$

$$q_{e,d+} = \rho\, a\, L\, K_{m,d}(e_d - e_{d+\Lambda})/p_d\Lambda \quad \text{(positive up)} \tag{27}$$

$$q_{e,d-} = \rho\, a\, L\, K_{m,d}(e_d - e_{d-\Lambda})/p_d\Lambda \quad \text{(positive down)} \tag{28}$$

$$e_d = e_{d,s} - \frac{q_{e,d+}}{\xi} \quad ;\ q_{e,d+} > 0 \tag{29}$$

$$e_d = e_{d,s};\ q_{e,d+} < 0 \tag{30}$$

$$e_{d,s} = 6.11 \times 10^{\iota};\ \iota = \frac{7.5T_d}{237.3 + T_d} \tag{31}$$

$$\tau_{x,d} = \rho\, K_{m,d}\ \frac{(u_{d+\Lambda} - u_{d-\Lambda})}{d(\ln(d+\Lambda) - \ln(d-\Lambda))} \tag{32}$$

$$\tau_{y,d} = \rho K_{m,d} \frac{(v_{d+\Lambda} - v_{d-\Lambda})}{d(\ln(d+\Lambda) - \ln(d-\Lambda))} \tag{33}$$

$$S_{d+\Lambda} = (u_{d+\Lambda}^{2} + v_{d+\Lambda}^{2})^{1/2} \tag{34}$$

$$Ri_{d+\Lambda} = \frac{\Lambda g(T_{d+\Lambda} - T_d)}{\overline{T}(S_{d+\Lambda} + 300)^2} \tag{35}$$

$$\beta = 1.003 - 1.163Ri_{d+\Lambda} - 9.627Ri_{d+\Lambda}^2 \tag{36}$$

$$K_{m,d+\Lambda} = \frac{(\Lambda)^{\beta}(1-\beta)k^2 z_o^{(1-\beta)} S_{d+\Lambda}}{[(\frac{\Lambda}{z_o})^{(1-\beta)} - 1]} \tag{37}$$

$$\log z_o = -1.24 + 1.19 \log d \tag{38}$$

C. Forest Section

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - g \frac{\partial h}{\partial x} + fv + \frac{1}{\rho} \frac{\partial \tau_x}{\partial z} + \frac{1}{\rho} F_x \tag{1f}$$

$$\frac{\partial v}{\partial t} = -u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - g \frac{\partial h}{\partial y} - fu + \frac{1}{\rho} \frac{\partial \tau_y}{\partial z} + \frac{1}{\rho} F_y \tag{2f}$$

$$\cdot c = -u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} - \frac{1}{\rho C_p} \frac{\partial q_c}{\partial z} + R \tag{3f}$$

$$\frac{\partial e}{\partial t} = -u \frac{\partial e}{\partial x} - v \frac{\partial e}{\partial y} - \frac{p}{\rho a L} \frac{\partial q_e}{\partial z} + M \tag{4f}$$

$$p = p_o - \rho g z \tag{5f}$$

$$f = 2\omega \sin \phi \tag{6f}$$

$$\tau_x = \rho K_m \frac{\partial u}{\partial z} \tag{7f}$$

$$\tau_y = \rho K_m \frac{\partial v}{\partial z} \tag{8f}$$

$$F_x = 1/2\rho A\ C_D\ u_j^2 \tag{9f}$$

$$F_y = 1/2\rho A\ C_D\ v_j^2 \tag{10f}$$

$$q_c = -\ \rho C_p K_h \frac{\partial T}{\partial z} \tag{11f}$$

$$q_e = -\ \rho L K_v \frac{\partial q}{\partial z} \tag{12f}$$

$$q = \frac{ae}{p} \tag{13f}$$

$$R = \frac{1}{C_p} \frac{dQ}{dt} \tag{14f}$$

$$\rho = \left(\frac{p}{R_a T}\right)_{t=0} \tag{15f}$$

$$K_m = K_h = K_v \tag{16f}$$

$$K_m = K_{m,\Lambda'} + \frac{K_{m,d-\Lambda} - K_{m,\Lambda'}}{(d - \Lambda) - \Lambda'} (z - \Lambda') \tag{17f}$$

D. Forest Surface Section

$$q_{c,o} + q_{e,o} + q_{s,o} - R_N = 0 \tag{18f}$$

$$R_N = S_N + L_N \tag{19f}$$

$$S_N = \chi[I\ \psi \cos\zeta\ e^{-N_{F_c}}](1 - J) \tag{20f}$$

$$\cos\zeta = \sin\phi \sin\delta + \cos\phi \cos\delta \cos H \tag{21f}$$

$$H = 15(t - 12) \tag{22f}$$

$$L_N = \sigma T_{\Lambda'}^4 (m + n\sqrt{e_{\Lambda'}}) - \varepsilon\sigma T_o^4 \tag{23f}$$

$$e_o = e_{o,s} - \frac{q_{e,o}}{s_o} \qquad q_{e,o} > 0 \tag{24f}$$

$$e_o = e_{o,s} \qquad q_{e,o} \leq 0 \tag{25f}$$

$$T_o' = T_o - Gq_{s,o} \tag{26f}$$

$$q_{e,o} = \rho a L D_{\Lambda'}(e_o - e_{\Lambda'})/p_o \tag{27f}$$

$$q_{c,o} = \rho C_p D_{\Lambda'}(T_o - T_{\Lambda'}) \tag{28f}$$

$$q_{s,o} = \left(\frac{\pi\lambda\mu}{P}\right)^{1/2}(T_o' - T_s') + \left(\frac{P\lambda\mu}{4\pi}\right)^{1/2} \frac{dT_o'}{dt} \tag{29f}$$

$$\tau_{x,o} = \rho D_{\Lambda'} u_{\Lambda'} \tag{30f}$$

$$\tau_{y,o} = \rho D_{\Lambda'} v_{\Lambda'} \tag{31f}$$

$$e_{o,s} = 6.11 \times 10^{\iota} \; ; \quad \iota = \frac{7.5T_o}{237.3 + T_o} \tag{32f}$$

$$S_{\Lambda'} = (u_{\Lambda'}^2 + v_{\Lambda'}^2)^{1/2} \tag{33f}$$

$$Ri_{\Lambda'} = \frac{\Lambda' g(T_{\Lambda'} - T_o)}{\overline{T}(S_{\Lambda'} + 300)^2} \tag{34f}$$

$$\beta = 1.003 - 1.163Ri_{\Lambda'} - 9.627Ri_{\Lambda'}^2 \tag{35f}$$

$$D_{\Lambda'} = \left[\frac{k(1 - \beta)}{\left(\frac{\Lambda'}{z_o}\right)^{(1-\beta)} - 1}\right]^2 S_{\Lambda'} \tag{36f}$$

$$K_{m,\Lambda'} = \frac{(\Lambda')^{\beta}(1 - \beta)k^2 z_o^{(1-\beta)} S_{\Lambda'}}{\left[\left(\frac{\Lambda'}{z_o}\right)^{(1-\beta)} - 1\right]} \tag{37f}$$

APPENDIX B

A. Free Air Section

$$u_j = \int \left[- \left(\alpha' u - \beta' v\right)_j - g \left(\frac{\partial h}{\partial x}\right)_j + f v_j + \frac{\left(\tau_{x,jk} - \tau_{x,ij}\right)}{\rho \ \Delta z_j} \right] \quad \text{(a1)}$$

$$v_j = \int \left[- \left(\alpha' v + \beta' u\right)_j - g \left(\frac{\partial h}{\partial x}\right)_j - f u_j + \frac{\left(\tau_{y,jk} - \tau_{y,ij}\right)}{\rho \ \Delta z_j} \right] \quad \text{(a2)}$$

$$T_j = \int \left[- \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right)_j - \frac{\left(q_{c,jk} - q_{c,ij}\right)}{\rho C_p \ \Delta z_j} + R \right] \quad \text{(a3)}$$

$$e_j = \int \left[- \left(u \frac{\partial e}{\partial x} + v \frac{\partial e}{\partial y}\right)_j - \frac{p_j \left(q_{e,jk} - q_{e,ij}\right)}{\rho a L \ \Delta z_j} \right] \quad \text{(a4)}$$

$$p_j = p_o - \rho g z_j \quad \text{(a5)}$$

$$\tau_{x,ij} = \frac{\rho}{z_j - z_i} K_{m,ij} \left(u_j - u_i\right)$$

(a7)

$$\tau_{x,jk} = \frac{\rho}{z_k - z_j} K_{m,jk} \left(u_k - u_j\right)$$

where $i = j - 1$, $k = j + 1$

$$\tau_{y,ij} = \frac{\rho}{z_j - z_i} K_{m,ij} \left(v_j - v_i\right)$$

$$\tau_{y,jk} = \frac{\rho}{z_k - z_j} K_{m,jk} \left(v_k - v_j\right) \tag{a8}$$

$$q_{c,ij} = -\frac{\rho C_p K_{h,ij}}{z_j - z_i} \left(T_j - T_i\right)$$

$$q_{c,jk} = -\frac{\rho C_p K_{h,jk}}{z_k - z_j} \left(T_k - T_j\right) \tag{a9}$$

$$q_{e,ij} = \frac{\rho a L \; K_{v,ij}}{\left(z_j - z_i\right) p_j} \left(\frac{p_j}{p_i} e_i - e_j\right)$$

$$q_{e,jk} = \frac{\rho a L \; K_{v,jk}}{\left(z_k - z_j\right) p_k} \left(\frac{p_k}{p_j} e_j - e_k\right) \tag{a10}$$

$$K_{m,ij} = b'_{ij} \; K_{m,d+\Lambda} \; , \qquad z_{ij} > d + \Lambda \tag{a15}$$

$$b'_{ij} = \left(\frac{Z}{\Lambda}\right) \left(\frac{Z}{Z - \Lambda}\right)^2 \left(\frac{z_{ij} - d}{Z}\right) \left(1 - \frac{z_{ij} - d}{Z}\right)^2 \tag{a16}$$

$$\left(\frac{\partial h}{\partial x}\right)_{j+1} = \left(\frac{\partial h}{\partial x}\right)_j + \frac{\Delta h_{n,n+1}}{\bar{T}} \left(\frac{\partial \bar{T}}{\partial x}\right)_{j,j+1} \tag{a17}$$

$$\left(\frac{\partial h}{\partial y}\right)_{j+1} = \left(\frac{\partial h}{\partial y}\right)_j + \frac{\Delta h_{n,n+1}}{\bar{T}} \left(\frac{\partial \bar{T}}{\partial y}\right)_{j,j+1} \tag{a18}$$

B. Free Air-Canopy Section

$$R_N = (q_{c,d+} + q_{e,d+}) + (q_{c,d-} + q_{e,d-}) \quad \text{(a19)}$$

$$R_N = (1 - J)\, I\psi \cos\zeta\, e^{-N}\Gamma_c + \sigma\, T^4_{d+\Lambda}\, (m + n\sqrt{e_{d+\Lambda}}) - \varepsilon\sigma T_d^4 \quad \text{(a20)}$$

$$\cos\zeta = \sin\phi \sin\delta + \cos\phi \cos\delta \cos(15[t - 12]) \quad \text{(a22)}$$

$$q_{c,d+} = \rho\, C_p\, K_{m,d}(T_d - T_{d+\Lambda})/\Lambda \quad \text{(positive up)} \quad \text{(a25)}$$

$$q_{c,d-} = \rho\, C_p\, K_{m,d}(T_d - T_{d-\Lambda})/\Lambda \quad \text{(positive down)} \quad \text{(a26)}$$

$$q_{e,d+} = \rho\, a\, L\, K_{m,d}(e_d - e_{d+\Lambda})/p_d\Lambda \quad \text{(positive up)} \quad \text{(a27)}$$

$$q_{e,d-} = \rho\, a\, L\, K_{m,d}(e_d - e_{d-\Lambda})/p_d\Lambda \quad \text{(positive down)} \quad \text{(a28)}$$

$$e_d = e_{d,s} - \frac{q_{e,d+}}{\xi}\; ; \; q_{e,d+} > 0 \quad \text{(a29)}$$

$$e_d = e_{d,s}\, ; \; q_{e,d+} < 0 \quad \text{(a30)}$$

$$e_{d,s} = 6.11 \times 10^{\iota}\; ; \; \iota = \frac{7.5T_d}{237.3 + T_d} \quad \text{(a31)}$$

$$\tau_{x,d} = \rho\, K_{m,d} \frac{(u_{d+\Lambda} - u_{d-\Lambda})}{d(\ln(d + \Lambda) - \ln(d - \Lambda))} \quad \text{(a32)}$$

$$\tau_{y,d} = \rho\, K_{m,d} \frac{(v_{d+\Lambda} - v_{d-\Lambda})}{d(\ln(d+\Lambda) - \ln(d-\Lambda))} \quad \text{(a33)}$$

$$S_{d+\Lambda} = (u_{d+\Lambda}^2 + v_{d+\Lambda}^2)^{1/2} \quad \text{(a34)}$$

$$Ri_{d+\Lambda} = \frac{\Lambda g(T_{d+\Lambda} - T_d)}{\bar{T}(S_{d+\Lambda} + 300)^2} \quad \text{(a35)}$$

$$\beta = 1.000 - 1.163\,Ri_{d+\Lambda} - 0.627\,Ri^2_{d+\Lambda} \tag{a36}$$

$$K_{m,d+\Lambda} = \frac{(\Lambda)^{\beta}(1-\beta)k^2 z_o^{(1-\beta)} S_{d+\Lambda}}{\left[\left(\frac{\Lambda}{z_o}\right)^{(1-\beta)} - 1\right]} \tag{a37}$$

C. Forest Section

$$u_j = \int \left[-(\alpha' u - \beta' v)_j - g\left(\frac{\partial h}{\partial x}\right)_j + f v_j + \frac{(\tau_{x,jk} - \tau_{x,ij})}{\rho \Delta z_j} + \frac{1}{2} C'_{D_j} u^2_{go} \right] \tag{a1f}$$

$$v_j = \int \left[-(\alpha' v + \beta' u)_j - \left(\frac{\partial h}{\partial y}\right)_j - f u_j + \frac{(\tau_{y,jk} - \tau_{y,ij})}{\rho \Delta z_j} + \frac{1}{2} C'_{Dj} v^2_{go} \right] \tag{a2f}$$

$$T_j = \int \left[-\left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right)_j - \frac{(q_{c,jk} - q_{c,ij})}{\rho C_p \Delta z_j} + R \right] \tag{a3f}$$

$$e_j = \int \left[-\left(u \frac{\partial e}{\partial x} + v \frac{\partial e}{\partial y}\right)_j - \frac{(q_{e,jk} - q_{e,ij})}{\rho a L \Delta z_j} + \cdots \right] \tag{a4f}$$

$$p_j = p_o - \rho g z_j \tag{a5f}$$

$$\tau_{x,ij} = \frac{\rho}{z_j - z_i} K_{m,ij} (u_j - u_i)$$

$$\tau_{x,jk} = \frac{\rho}{z_k - z_j} K_{m,jk} (u_k - u_j) \tag{a7f}$$

$$\tau_{y,ij} = \frac{\rho}{z_j - z_i} K_{m,ij} \left(v_j - v_i\right)$$

$$\tau_{y,jk} = \frac{\rho}{z_k - z_j} K_{m,jk} \left(v_k - v_j\right) \qquad \text{(a8f)}$$

$$u_{go} = -\frac{g}{f}\left(\frac{\partial h}{\partial y}\right)_o \qquad \text{(a9f)}$$

$$v_{go} = \frac{g}{f}\left(\frac{\partial h}{\partial x}\right)_o \qquad \text{(a10f)}$$

$$q_{c,ij} = -\frac{\rho C_p K_{h,ij}}{z_j - z_i}\left(T_j - T_i\right)$$

$$q_{c,jk} = -\frac{\rho C_p K_{h,ij}}{z_k - z_j}\left(T_k - T_j\right) \qquad \text{(a11f)}$$

$$q_{e,ij} = \frac{\rho a L K_{v,ij}}{\left(z_j - z_i\right) p_j}\left(\frac{p_i}{p_i} e_i - e_j\right)$$

$$q_{e,jk} = \frac{\rho a L K_{v,jk}}{\left(z_k - z_j\right) p_k}\left(\frac{p_k}{p_j} e_j - e_k\right) \qquad \text{(a12f)}$$

$$K_{m,ij} = K_{m,\Lambda'} + \frac{K_{m,d-\Lambda} - K_{m,\Lambda'}}{(d - \Lambda) - \Lambda'}\left(z_{ij} - \Lambda'\right) \qquad \text{(a17f)}$$

D. Forest Surface Section

$$R_N = q_{c,o} + q_{e,o} + q_{s,o} \qquad \text{(a18f)}$$

$$R_N = \chi(1 - J) I \psi \cos \zeta e^{-N} F_c + \sigma T^4_{\Lambda'}\left(m + n\sqrt{e'_{\Lambda'}}\right) - \epsilon\sigma T^4_o \qquad \text{(a19f)}$$

$$\cos \zeta = \sin \phi \sin \delta + \cos \varphi \cos \delta \cos (15[t - 12]) \qquad \text{(a21f)}$$

$$e_o = e_{o,s} - \frac{q_{e,o}}{s_o} \qquad q_{e,o} > 0 \qquad \text{(a24f)}$$

$$e_o = e_{o,s} \qquad q_{e,o} \leqslant 0 \qquad \text{(a25f)}$$

$$T_o' = T_o - Gq_{s,o} \qquad \text{(a26f)}$$

$$q_{e,o} = \rho \bar{a} L D_{\Lambda'} (e_o - e_{\Lambda'})/p_o \qquad \text{(a27f)}$$

$$q_{c,o} = \rho C_p D_{\Lambda'} (T_o - T_{\Lambda'}) \qquad \text{(a28f)}$$

$$T_o' = \int \left[2\left(\frac{\pi}{P}\right)^{1/2} \frac{q_{s,o}}{\sqrt{\lambda \mu}} - \frac{2\pi}{P} (T_o' - T_s') \right] \qquad \text{(a29f)}$$

$$\tau_{x,o} = \rho D_{\Lambda'} u_{\Lambda'} \qquad \text{(a30f)}$$

$$\tau_{y,o} = \rho D_{\Lambda'} v_{\Lambda'} \qquad \text{(a31f)}$$

$$e_{o,s} = 6.11 \times 10^{\iota} \; ; \; \iota = \frac{7.5T_o}{237.3 + T_o} \qquad \text{(a32f)}$$

$$S_{\Lambda'} = (u_{\Lambda'}^2 + v_{\Lambda'}^2)^{1/2} \qquad \text{(a33f)}$$

$$Ri_{\Lambda'} = \frac{\Lambda' g (T_{\Lambda'} - T_o)}{\bar{T}(S_{\Lambda'} + 300)^2} \qquad \text{(a34f)}$$

$$\beta = 1.003 - 1.163 Ri_{\Lambda'} - 9.627 Ri_{\Lambda'}^2 \qquad \text{(a35f)}$$

$$D_{\Lambda'} = \left[\frac{k(1 - \beta)}{\left(\frac{\Lambda'}{z_o}\right)^{(1-\beta)} - 1} \right]^2 S_{\Lambda'} \qquad \text{(a36f)}$$

$$K_{m,\Lambda'} = \frac{(\Lambda')^{\beta} (1 - \beta) k^2 z_o^{(1-\beta)} S_{\Lambda'}}{\left[\left(\frac{\Lambda'}{z_o}\right)^{(1-\beta)} - 1\right]}, \; \beta \neq 1 \qquad \text{(a37f)}$$

$$K_{m,\Lambda'} = \frac{150k^2 S_{\Lambda'}}{\ell n(\frac{150}{z_o})}, \ \beta = 1 \tag{a37f}$$

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13. ABSTRACT

This report summarizes the activities carried out under Signal Corps Contract No. DAAB07-68-C-0381 (Texas A & M Research Foundation Project 586) during the contract period 15 June 1969 through 15 December 1969.

Activities during this period have centered on preparation of the equations for the forested boundary layer for solution on the general purpose analog computer at Texas A & M University. These expressions, which were presented in Semi-Annual Report 2, have been programmed for a seven-level simulation, three in the forest and four in the free air above, and for the surface and free air-canopy interfaces. The wiring of the patchboards is proceeding as the wiring diagrams are completed.

Some qualitative diffusion tests were carried out in the tropical forest in the Panama Canal Zone. Visual and photographic observations have been summarized.

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